Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Assessing the relevance of systematics in the LiteBIRD experiment

Andrea Sabatucci

Spoke 3 General Meeting, Elba 5-9 / 05, 2024

Scientific Rationale

LiteBIRD -**Lite** (Light) satellite for the studies of **B**-mode polarization and **I**nflation from cosmic background **R**adiation **D**etection- **Experiment**→ measure CMB angular power spectrum in seek of B-modes

CMB anisotropies → Inflation Hypothesis

Inflation→ Tensor Perturbations→ Primordial Gravitational Waves→B-mode polarization

Polarization anisotropies (Linear polarization)
- → **E-modes** (symmetric under parity transformation w.r.t. the propagation direction)
- → **B-modes** (antisymmetric under parity transformation w.r.t. the propagation direction)

Progress of Theoretical and Experimental Physics, Volume 2023, Issue 4, April 2023, 042F01, https://doi.org/10.1093/ptep/ptac150

Technical Objectives, Methodologies and Solutions

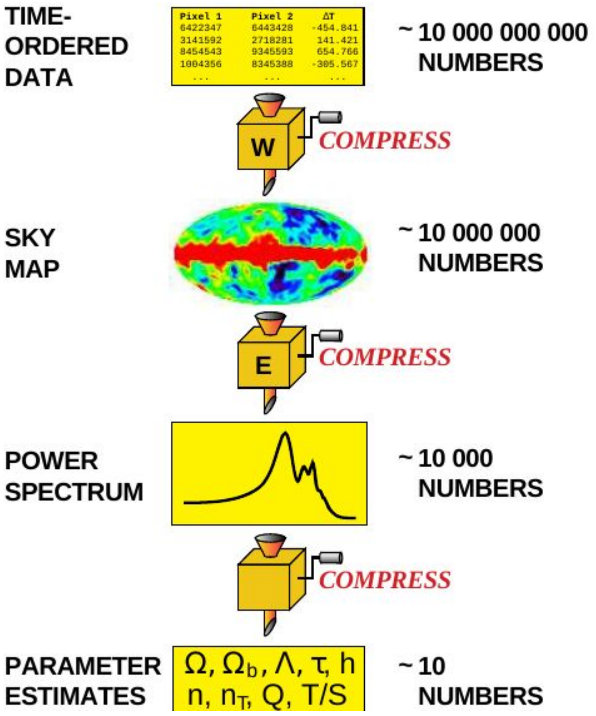
-Objective: Recover parameters from Time Ordered Data (TOD)

The analysis pipeline has the objective to compress a large amount of data to extract few parameters.

This is an expensive process→ simulations with mocked data will help us in preparation of the actual data.

- Addressing the role of systematic effects is crucial in order to define a complete analysis pipeline.

Max Tegmark and Angelica de Oliveira-Costa
Phys. Rev. D 64, 063001 – Published 16 August 2001



Technical Objectives, Methodologies and Solutions

Crosstalk → Different detectors mutually interact with each others
Crosstalk across different frequency channels will mix different amount of foreground components → **biased results**

Crosstalk will mix the TOD according to →

$$\tilde{d}^i = \sum_j X^{ij} d^j$$

Large number of detectors (~5000) and large number of time samples (~10^9) → Big Data and parallelization problem

Experimentalists can reduce the crosstalk in the design, **our objective** is to address the amount of bias injected into the signal from a given crosstalk matrix.

Our Final Task is to perform simulations with different crosstalk matrices in order to study their impact on the final results.

Timescale, Milestones and KPIs

Elba, May 2024

Milestone 7-8

- Study the literature
- Understand the problem
- Develop a scientific project

Milestone 9 (June 2024-October 2024)

- **Study the crosstalk and how to implement it**
- **Debug**

→ **KPIs**: simulation reports

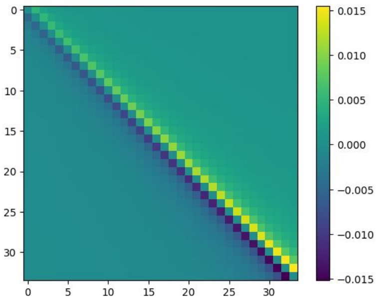
Milestone 10 (-August 2025 ?)

- **Optimization**
- **Final Simulations**
- **Study the results**
- **Write a Paper**
- **Release on Github**

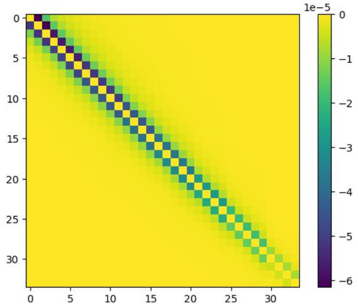
→ **KPIs**: Simulation reports, draft of the paper and/or github package

Technical Objectives, Methodologies and Solutions

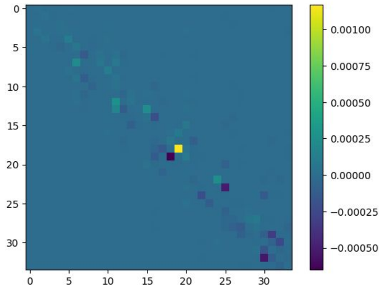
- We have considered three crosstalk matrices corresponding to as many crosstalk effects.*
- We are considering only the detectors connected to the Squid 0 of the LF12 wafer in the Low Frequency Telescope (LFT)**



Common Impedance

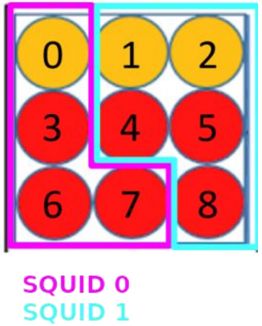


Carrier Leakage

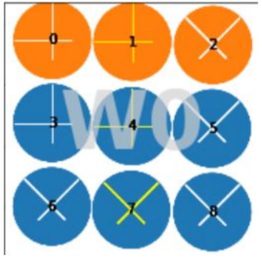


Coil mutual inductance

SQUID Mapping



Pixel orientation



*Crosstalk matrices have been computed by Eugenia Di Giorgi (PhD student in Pisa)
**We still refer to the old design of the LiteBIRD telescope, that is currently being revised.

Technical Objectives, Methodologies and Solutions

Simulation Pipeline

- Choose the detectors (a subset of those in LF12 SQUID 0)
- Define Input Sky map
- Impose a scanning strategy
- Generate Time Ordered Data (TOD)
- Extract a submatrix from the crosstalk matrix for the detectors involved
- Compute the TOD including crosstalk by performing a Matrix vector multiplication at any given time sample

$$\tilde{d}^i = \sum_j X^{ij} d^j$$

- Compute the sky map with a binned mapmaker using TOD both w/ and w/o crosstalk
- Compute the sky map associated with the difference between the TOD w/ and w/o crosstalk (crosstalk residual)
- Compute the power spectra

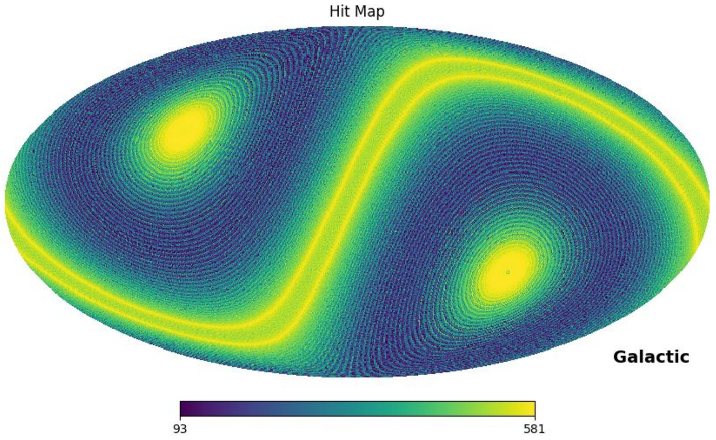
Main Objective: The Goal of LiteBIRD is to measure the CMB B-modes. If the power spectrum associated with crosstalk residuals is comparable with the CMB B-mode power spectrum this means that crosstalk can potentially affect the results, and must be mitigated.

Technical Objectives, Methodologies and Solutions

In the following we report the results some representative simulations

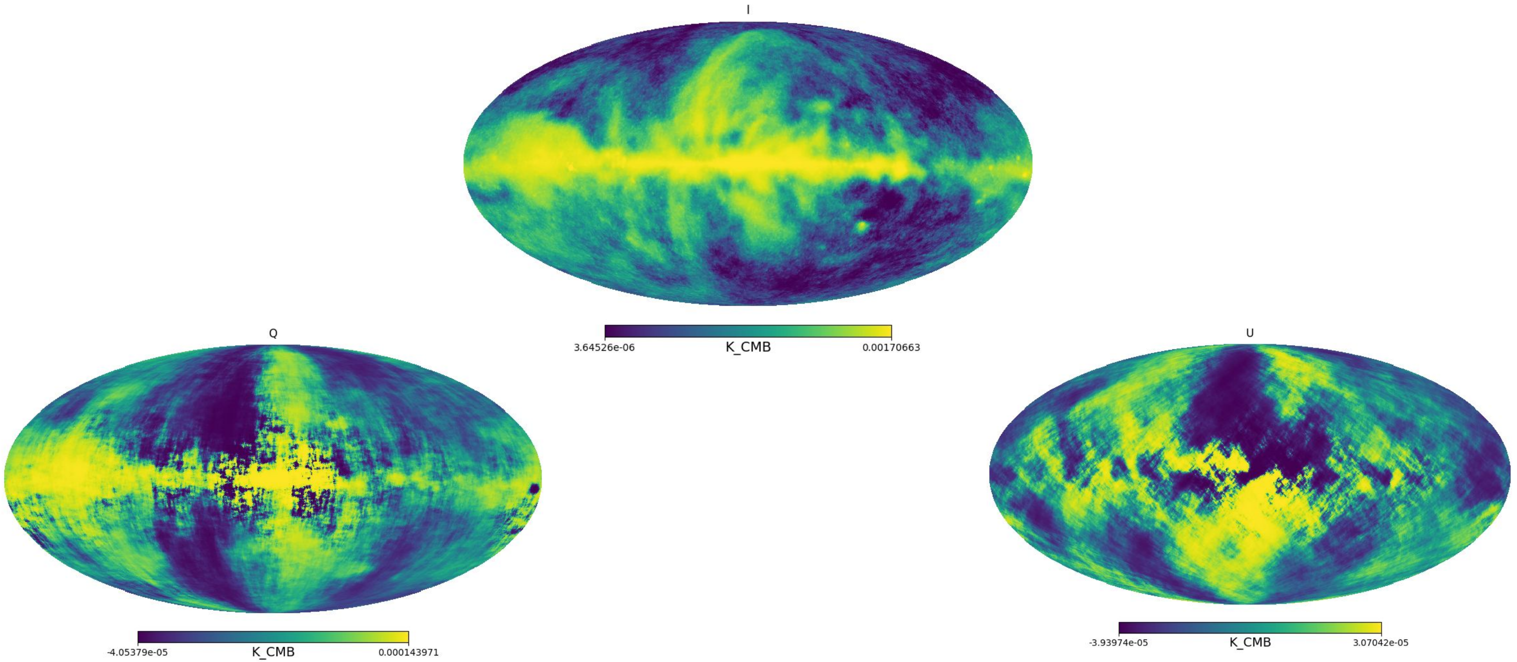
Setup

- 2 detectors at 40 GHz (orientation is defined case by case)
- Sky map: synchrotron radiation only
- Nside=128
- 1 year simulation
- 1 Hz sampling rate
- 2 different crosstalk matrices (carrier leakage and common impedance)



Technical Objectives, Methodologies and Solutions

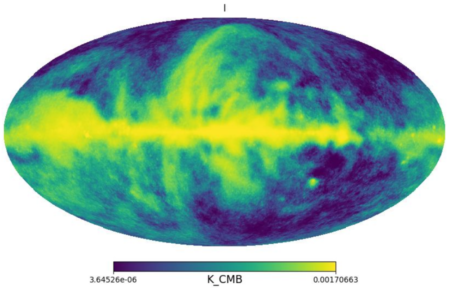
Injected synchrotron sky map at 40 GHz

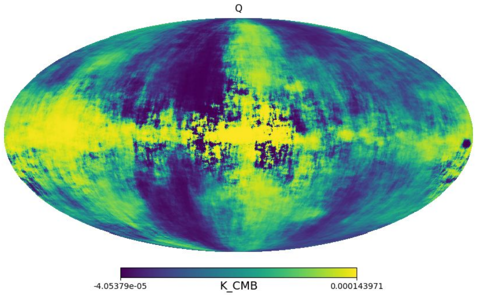


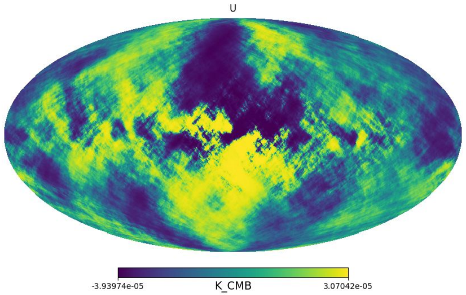
Carrier leakage crosstalk, π/2 mutual orientation

Reconstructed maps (no crosstalk)

$$\mathbf{m} = M^{-1}\hat{P}^T C^{-1}\mathbf{d} \qquad M = \hat{P}^T C^{-1}\hat{P}$$

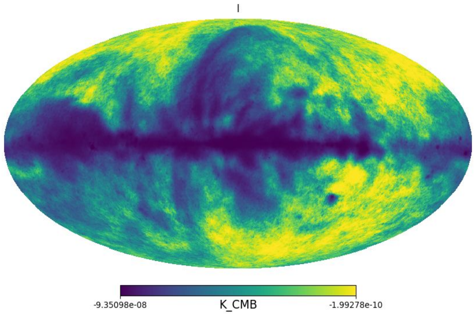


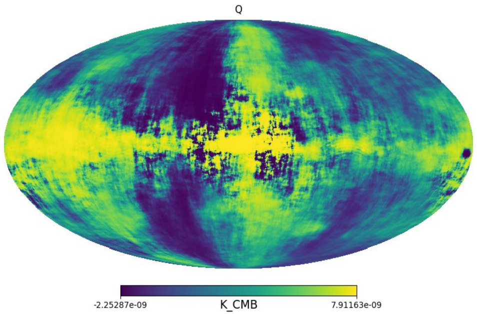


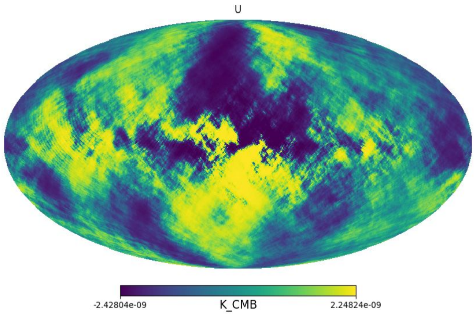


Crosstalk residual maps

$$\mathbf{\Delta m}_{tot} = M_{tot}^{-1}[P_1^T C_1^{-1} X_{12} d_2 + P_2^T C_2^{-1} X_{21} d_1]$$



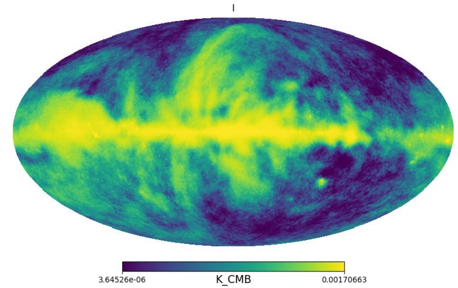


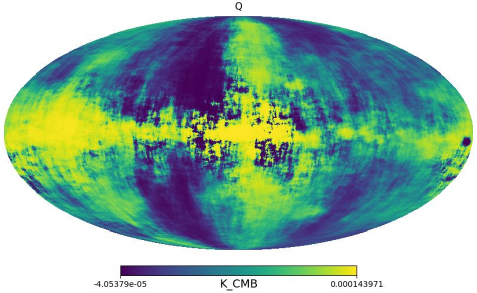


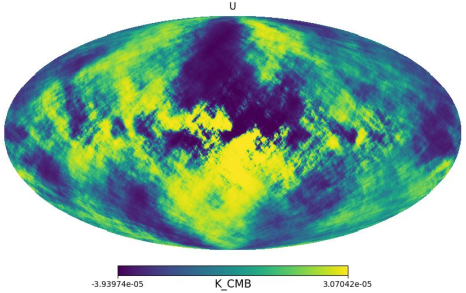
Common impedance crosstalk, π/2 mutual orientation

Reconstructed maps (no crosstalk)

$$\mathbf{m} = M^{-1}\hat{P}^T C^{-1}\mathbf{d} \qquad M = \hat{P}^T C^{-1}\hat{P}$$

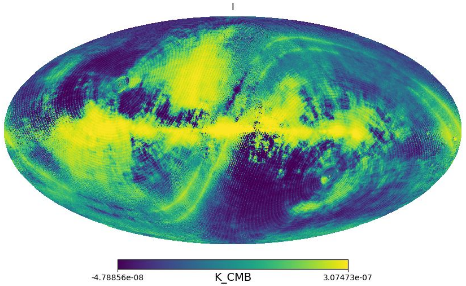


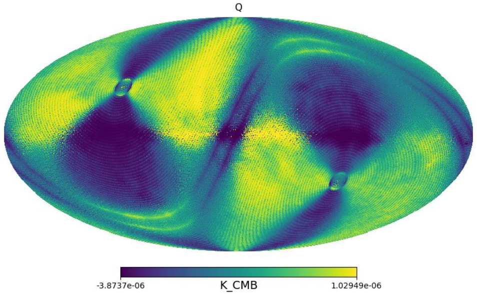


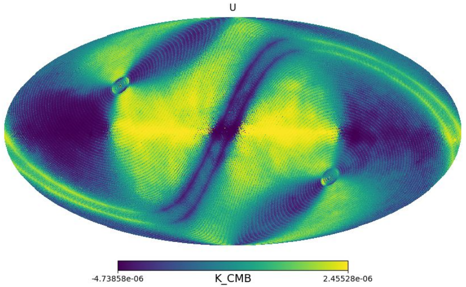


Crosstalk residual maps

$$\mathbf{\Delta m}_{tot} = M_{tot}^{-1}[P_1^T C_1^{-1} X_{12} d_2 + P_2^T C_2^{-1} X_{21} d_1]$$

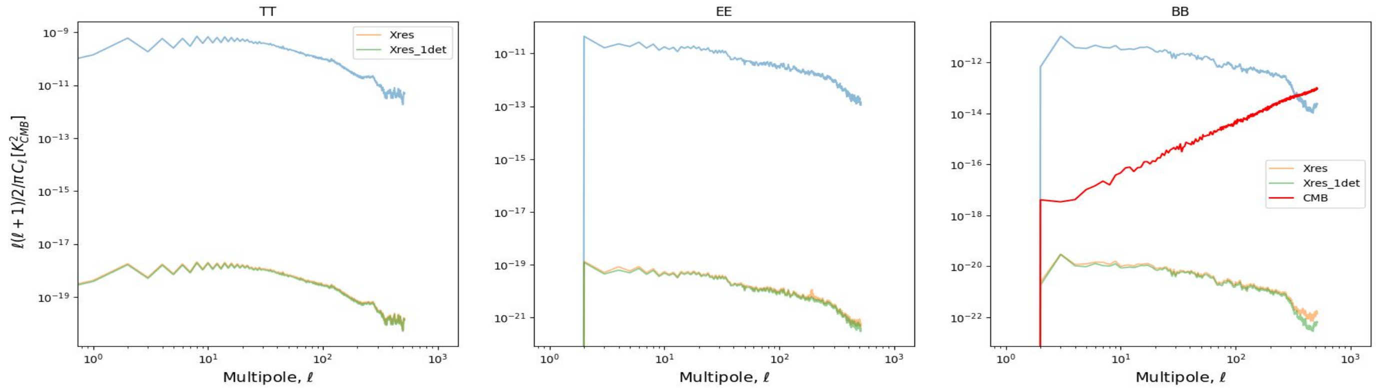






Accomplished Work, Results

Power spectra
Carrier Leakage

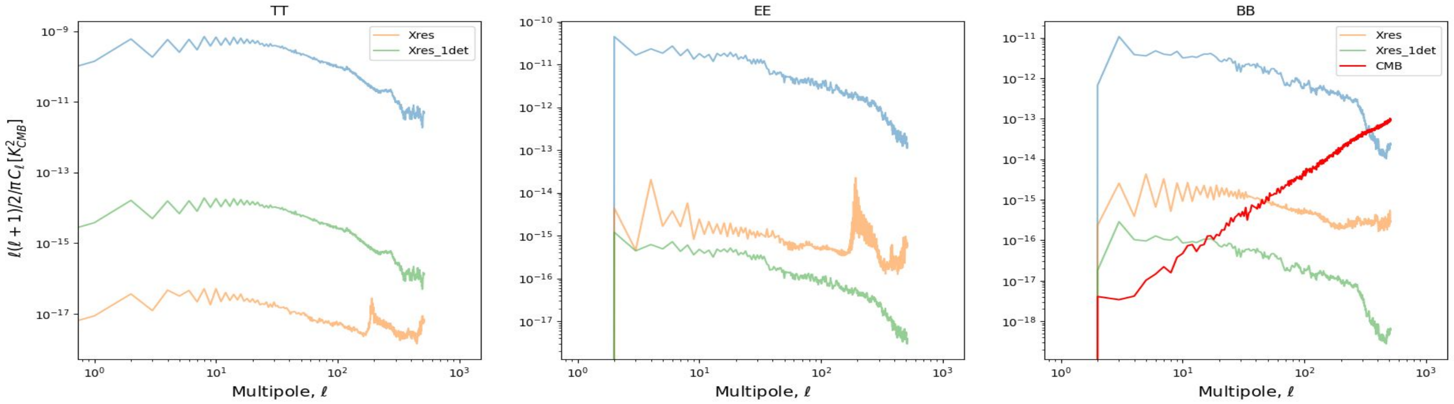


We can see that in this case the crosstalk residual in the BB-Power spectrum, which is the main object of the LiteBIRD experiment, lies well below the CMB BB-power spectrum, suggesting that its impact on the final result could be negligible.

Accomplished Work, Results

Power spectra

Common Impedance



In this case we can see that the crosstalk residual of Synchrotron emission in the BB power spectrum is comparable with the CMB BB-power spectrum due to gravitational lensing only. This is an indication that crosstalk effects has to be removed from the TOD before doing any kind of map making procedure, otherwise they can strongly affect the results.

Timescale, Milestones and KPIs

Milestone 9 (June 2024-October 2024)

- Study the crosstalk and how to implement it
- Implemented crosstalk in the simulation pipeline
- Obtained first results of the crosstalk effect on the B-mode power spectrum

→ **KPIs**: simulation reports

Milestone 10 (-December 2025)

- Full Simulations in HPC clusters with more detectors, higher sampling rate and map resolution.
- Define a mitigation strategy and implement it within the simulations
- Write a paper summarizing the results
- Release of the crosstalk package on the litebird_sim github

→ **KPIs**: Simulation reports, draft of the paper and/or github package

Next Steps and Expected Results

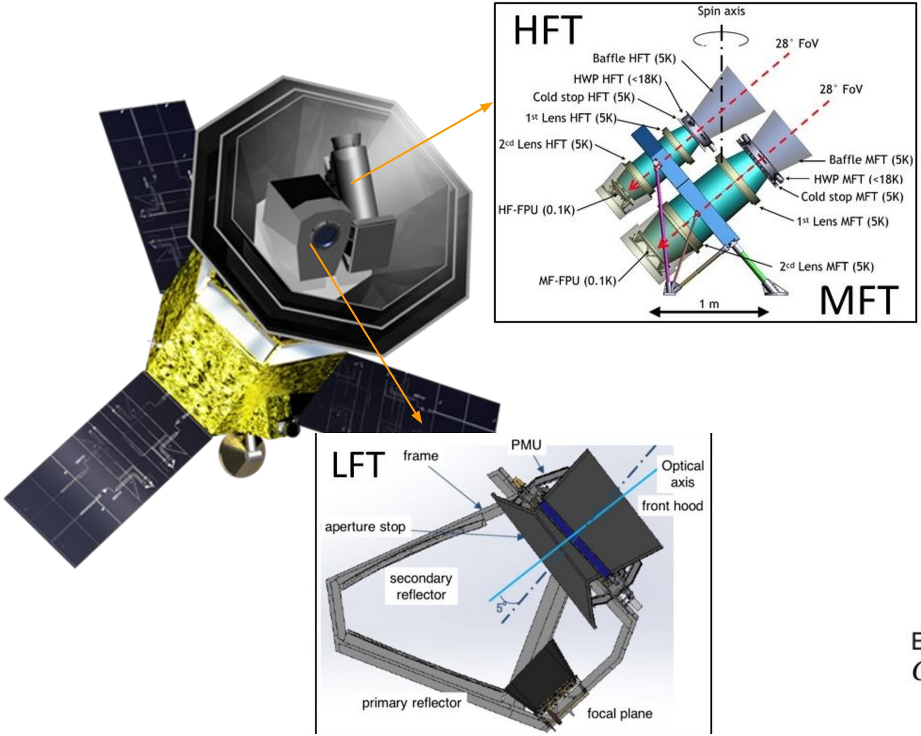
- **Perform more realistic simulations with a larger number of detectors, higher sampling rate and higher map resolution.**
- **Study and define a way to mitigate the crosstalk systematics**
- **Perform simulations to assess the efficiency of the defined mitigation strategy**

Next Steps and Expected Results

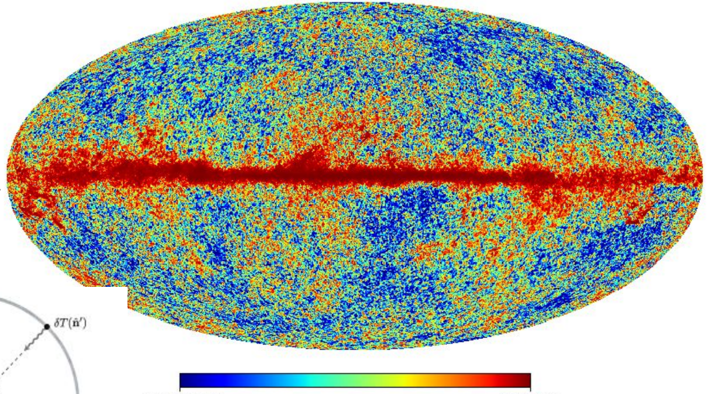
Thank you for your attention!

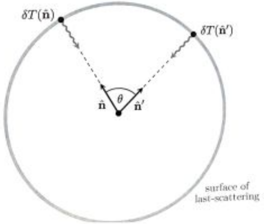
Backup Slides

Scientific Rationale



Planck map

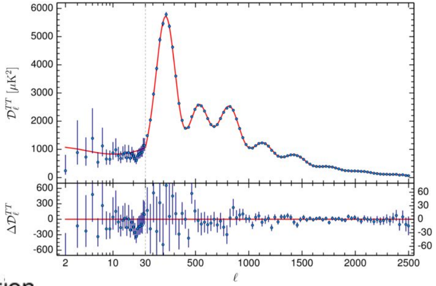




from Baumann, Cosmology

$$\Theta(\hat{n}) = \frac{T(\hat{n}) - T_0}{T_0}$$

Expansion in spherical harmonic



Build the average of the 2-point correlation function

$$C(\theta) = \langle \Theta(\hat{n})\Theta(\hat{n}') \rangle$$

Technical Objectives, Methodologies and Solutions

How to simulate the analysis pipeline? → LiteBIRD Simulation Framework

LiteBIRD simulation pipeline

Navigation

Contents:

Welcome to litebird_sim's documentation!

Contents:

The LiteBIRD simulation framework is a Python package that can simulate the data acquisition process for the three instruments that will be present onboard of the LiteBIRD Spacecraft.

↓

TOD Generation and analysis

↓

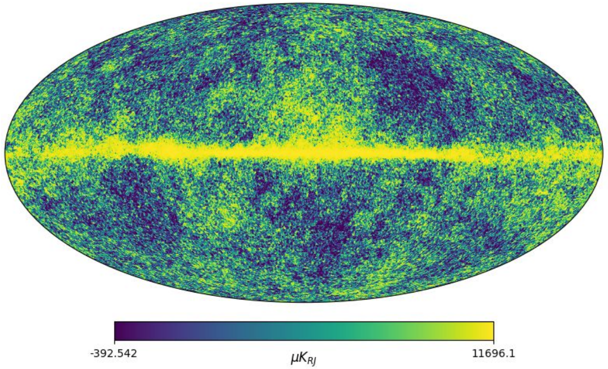
Some systematics, such as crosstalk, need to be added to the framework

https://litebird-sim.readthedocs.io/en/latest/index.html#

Technical Objectives, Methodologies and Solutions

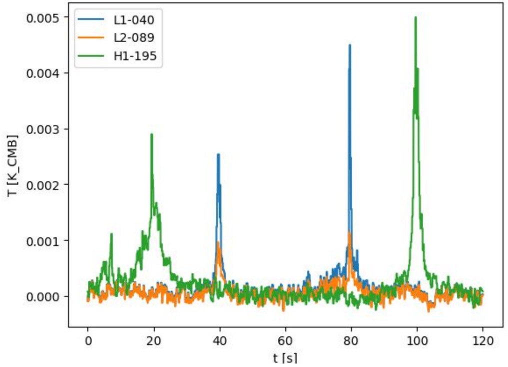
- **TOD is a time series of data points, indexed and in time order**. → LiteBIRD will sample the sky with a frequency ~19 Hz.
- In the actual experiment raw TOD will be used to build a sky map.
- In the Simulation Framework we proceed in the opposite direction

From an injected map



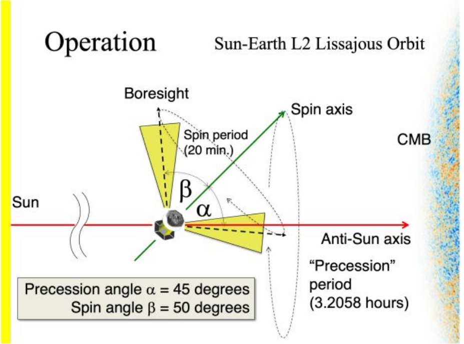
\+ Impose a scanning strategy →

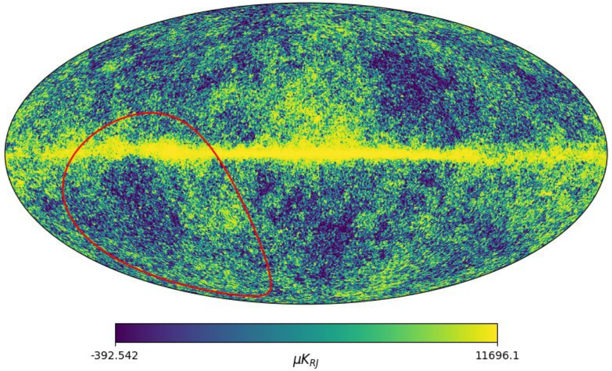
to TOD (numpy arrays)



Technical Objectives, Methodologies and Solutions

Scanning strategy





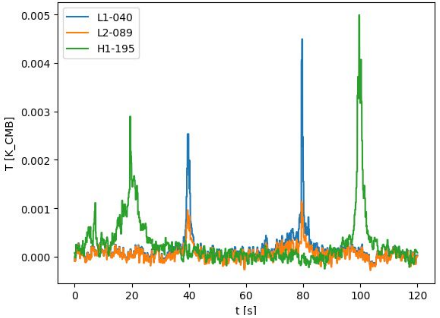
Pointing Matrix
(Nsample x 3Npixel)

TOD vector

noise vector

$$d_t = \sum_p A_{tp} m_p + n_t$$

input Sky map



Technical Objectives, Methodologies and Solutions

Once the TOD are generated (comprehensive of noise) we shall recover the sky map by "Inverting" the TOD equation .

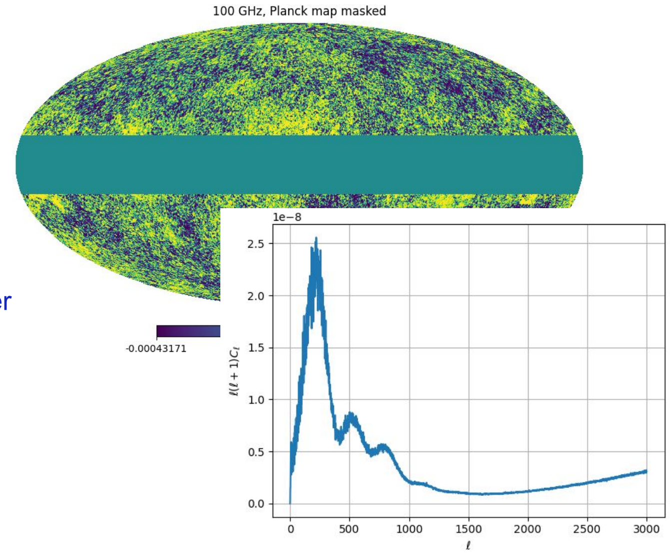
If only white noise

$$\hat{m} = \left(A^T C_w^{-1} A\right) A^T C_w^{-1} d$$

with

$$C_w^{-1} = \begin{pmatrix} \frac{1}{\sigma^2} & 0 & 0 & \cdots \\ 0 & \frac{1}{\sigma^2} & 0 & \cdots \\ 0 & 0 & \frac{1}{\sigma^2} & \\ \vdots & \vdots & & \ddots \end{pmatrix}$$

Finally recover the power spectrum from the reconstructed map (healpy library)



What is happening?

In order to understand what is happening we shall take a closer look at the map maker.

SPOILER: The discrepancy with the previous case is originated by the *antisymmetry* of the common impedance crosstalk matrix.

$$\mathbf{m} = M^{-1}\hat{P}^T C^{-1}\mathbf{t} \qquad M = \hat{P}^T C^{-1}\hat{P}$$

If we have more detectors, their TOD are appended end to end such that the output map is computed according to

$$\mathbf{m}_{tot} = M_{tot}^{-1}\begin{bmatrix} P_1^T & P_2^T \end{bmatrix}\begin{bmatrix} C_1^{-1} & 0 \\ 0 & C_2^{-1} \end{bmatrix}\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = M_{tot}^{-1}[P_1^T C_1^{-1} t_1 + P_2^T C_2^{-1} t_2]$$

$$M_{tot} = [P_1^T C_1^{-1} P_1 + P_2^T C_2^{-1} P_2] \equiv [M_1 + M_2]$$

Therefore, for the crosstalk residual we will have $\mathbf{\Delta m}_{tot} = M_{tot}^{-1}[P_1^T C_1^{-1} X_{12} t_2 + P_2^T C_2^{-1} X_{21} t_1]$

What is happening?

$$\mathbf{\Delta m}_{tot} = M_{tot}^{-1}[P_1^T C_1^{-1} X_{12} t_2 + P_2^T C_2^{-1} X_{21} t_1]$$

If we define $\bar{t_1} \equiv t_2$ as the TOD obtained by detector one, but observing a sky map given by $\bar{\boldsymbol{m}}$ (and similarily for $\bar{t}_2$). We have

$$\mathbf{\Delta m}_{tot} = M_{tot}^{-1}[P_1^T C_1^{-1} X_{12} \bar{t}_1 + P_2^T C_2^{-1} X_{21} \bar{t}_2] \tag{26}$$

that in the case of $X_{12} \approx X_{21}$ it becomes

$$\mathbf{\Delta m}_{tot} = M_{tot}^{-1}[P_1^T C_1^{-1} \bar{t}_1 + P_2^T C_2^{-1} \bar{t}_2] X_{12} = X_{12} \bar{\boldsymbol{m}} \tag{27}$$

But for the common impedence crosstalk matrix we have $X_{12} \approx -X_{21}$ yielding

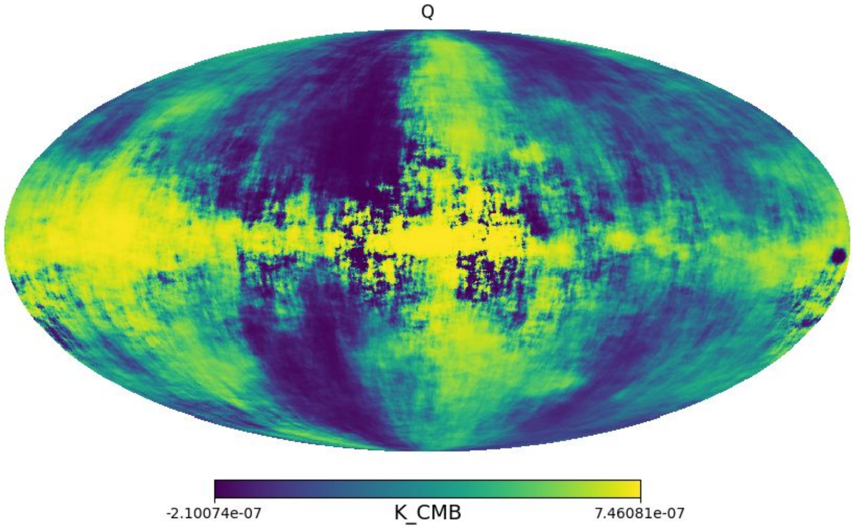
$$\mathbf{\Delta m}_{tot} = M_{tot}^{-1}[P_1^T C_1^{-1} \bar{t}_1 - P_2^T C_2^{-1} \bar{t}_2] X_{12} \neq X_{12} \bar{\boldsymbol{m}}$$

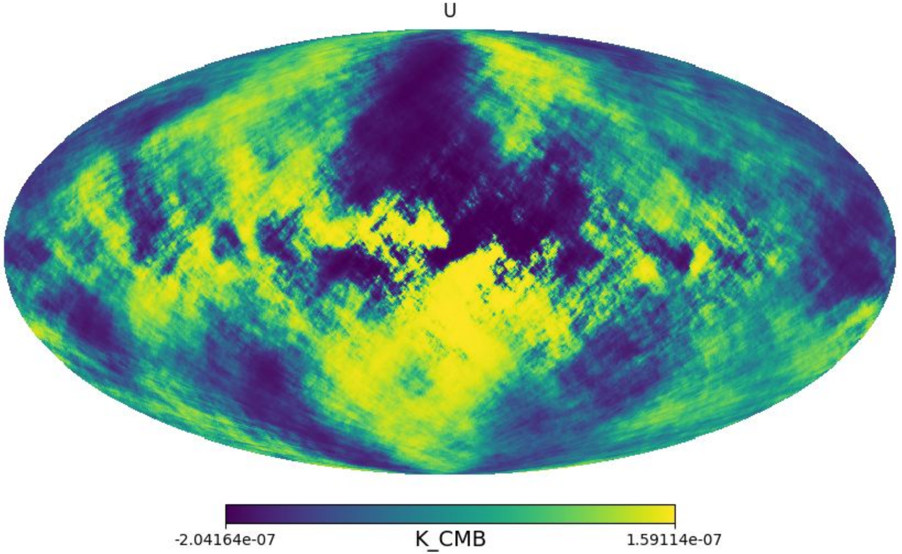
Instead of computing $\boldsymbol{\Delta m}_{tot}$ we can compute the residual for the TOD of only one detector, according to

$$\boldsymbol{\Delta m}_1 = M_1^{-1}[P_1^T C_1^{-1} X_{12} t_2]$$

Residual maps from the TOD of only one detector

$$\boldsymbol{\Delta m}_1 = M_1^{-1}[P_1^T C_1^{-1} X_{12} t_2]$$

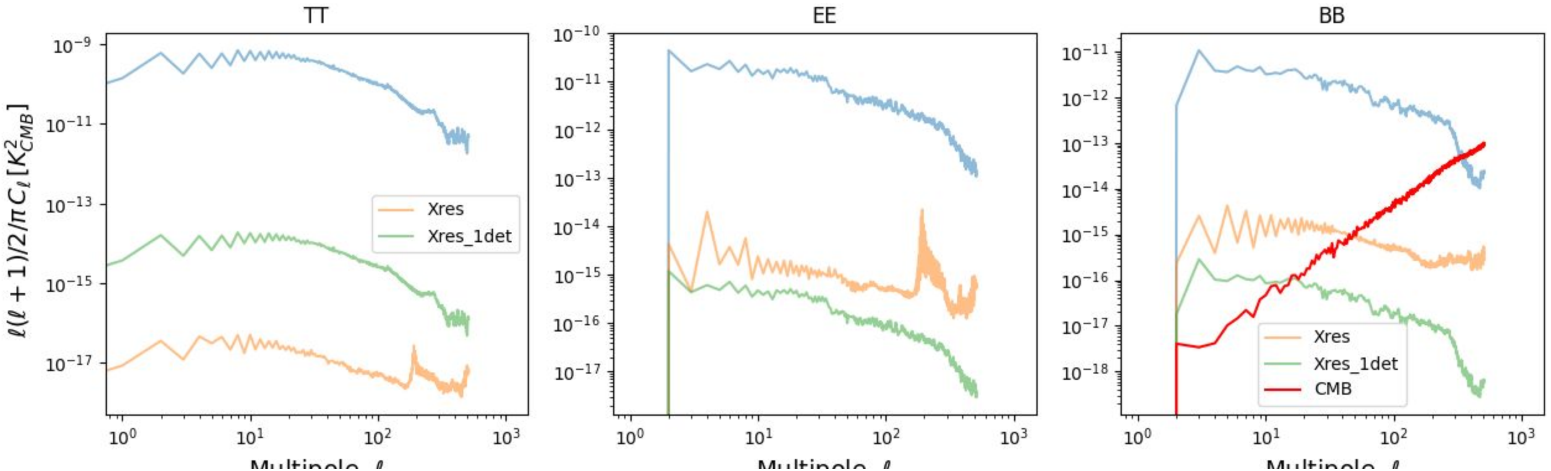




Exactly what we expected.

Power Spectra

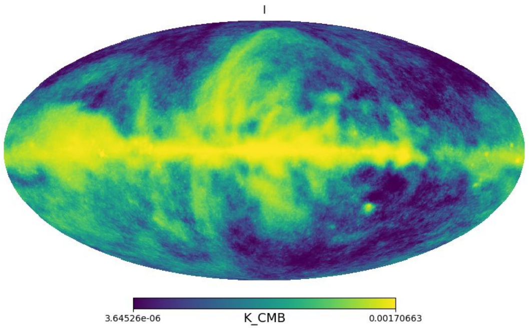
Blue lines represent the Synchrotron power spectrum

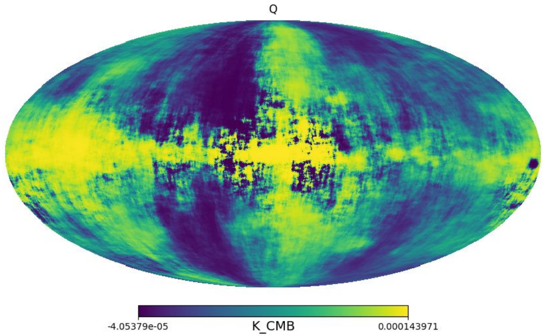


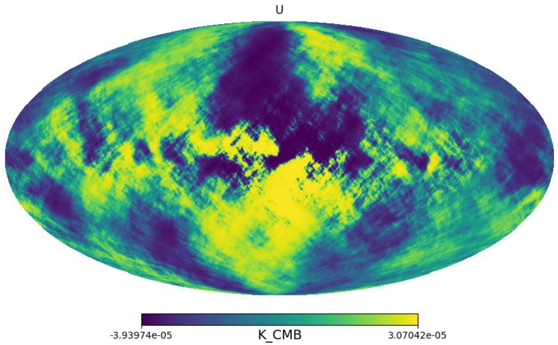
In this case we can see that the crosstalk residual of Synchrotron emission in the BB power spectrum is comparable with the CMB BB-power spectrum due to gravitational lensing only. This is an indication that crosstalk effects has to be removed from the TOD before doing any kind of map making procedure, otherwise they can potentially affect the results.

Two detectors oriented at pi/4

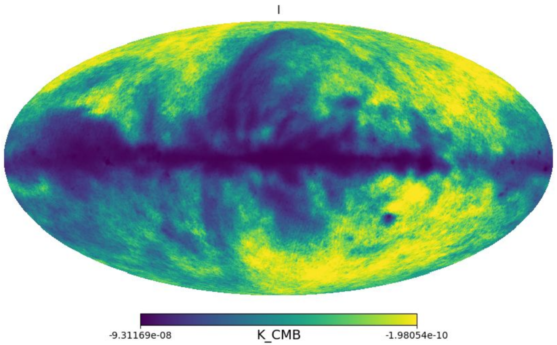
Carrier Leakage Crosstalk

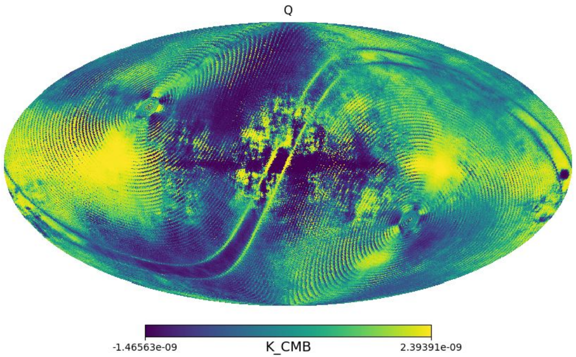


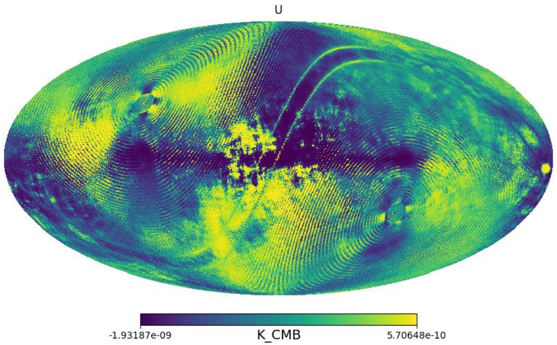




Crosstalk residual maps

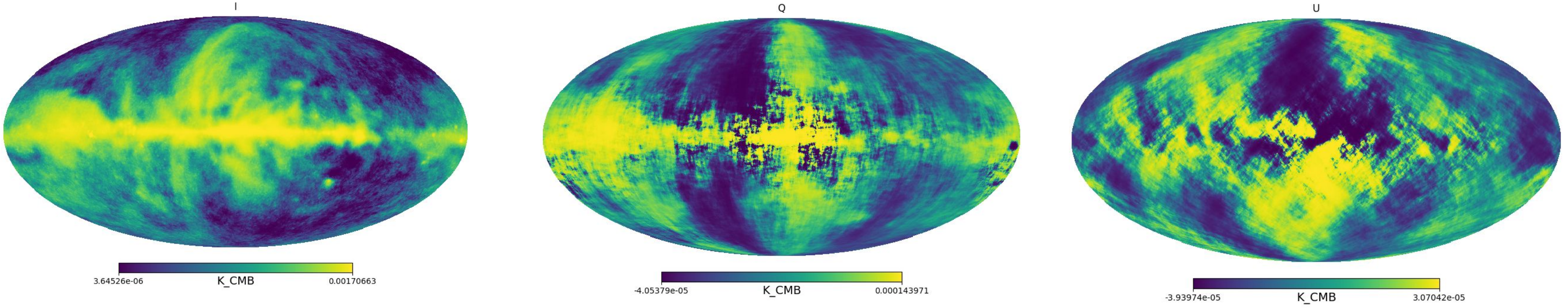




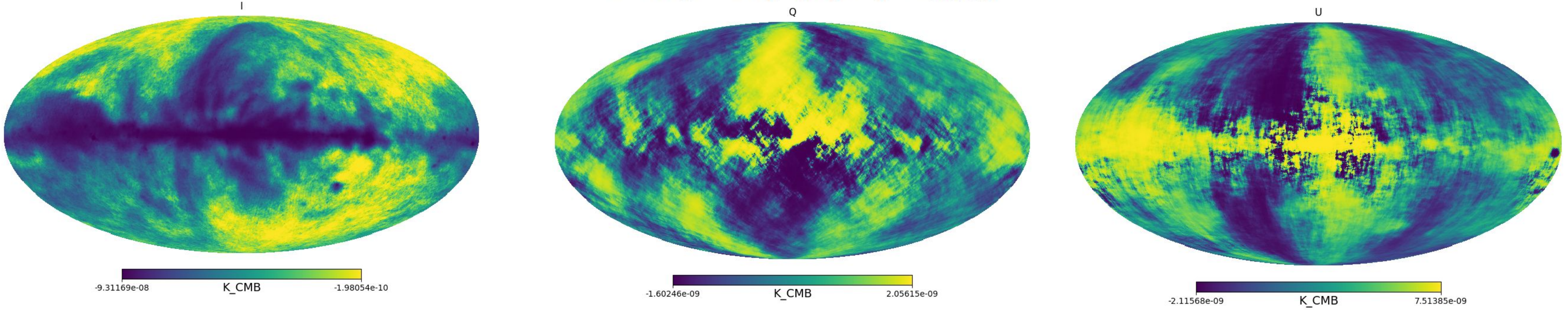


Residual maps from the TOD of only one detector

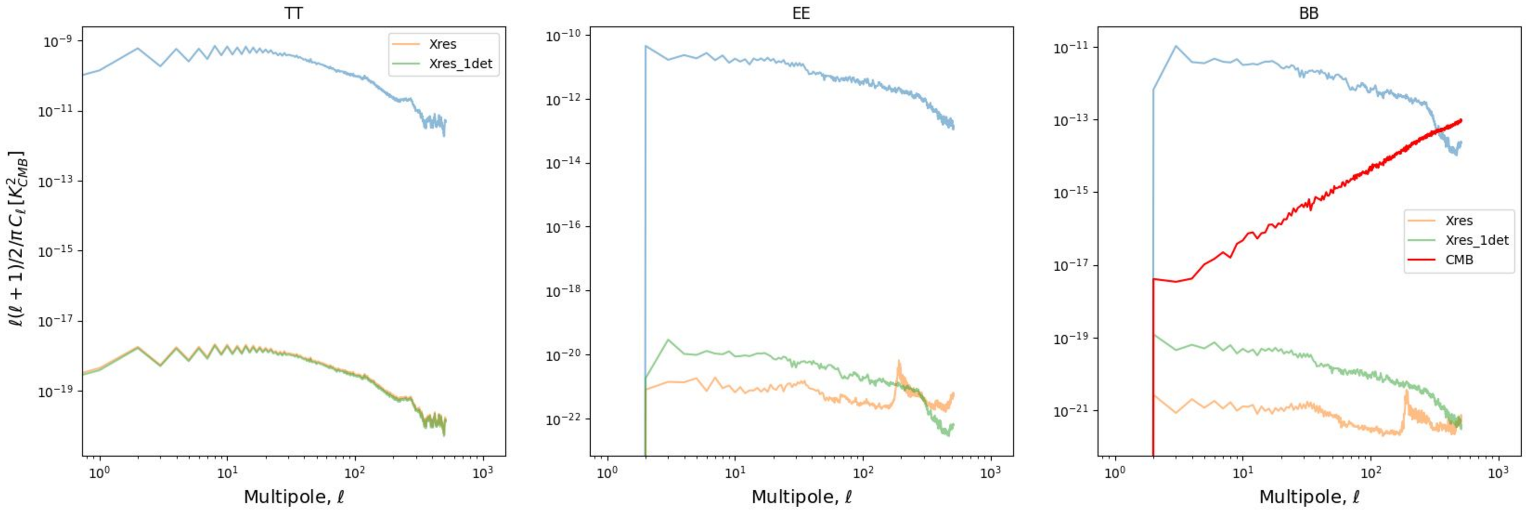
Input Sky maps



$$\Delta m_1 = M_1^{-1}[P_1^T C_1^{-1} X_{12} t_2]$$

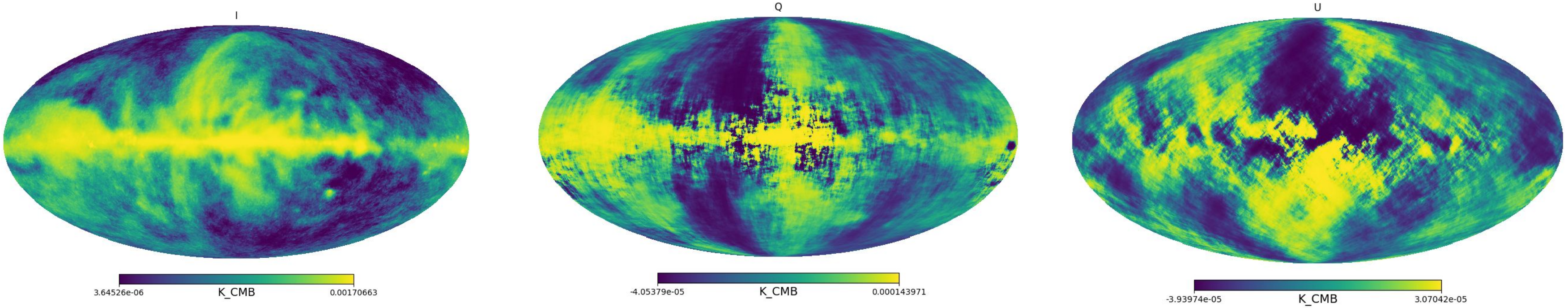


Power Spectra pi/4 carrier leakage

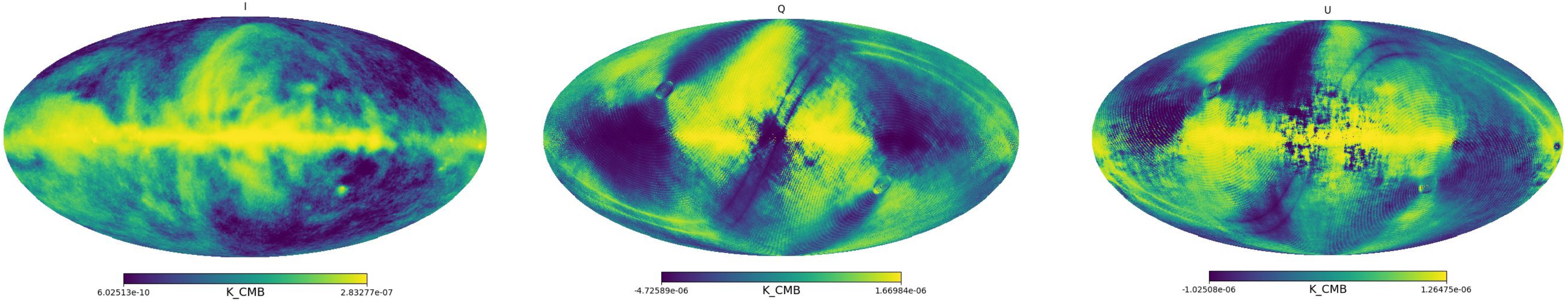


Two detectors oriented at pi/4

Common Impedance Crosstalk

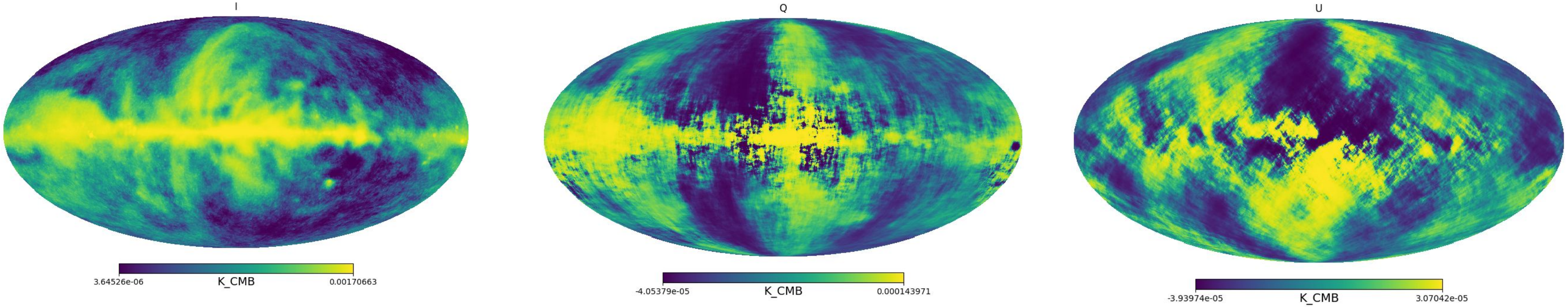


Crosstalk residual maps

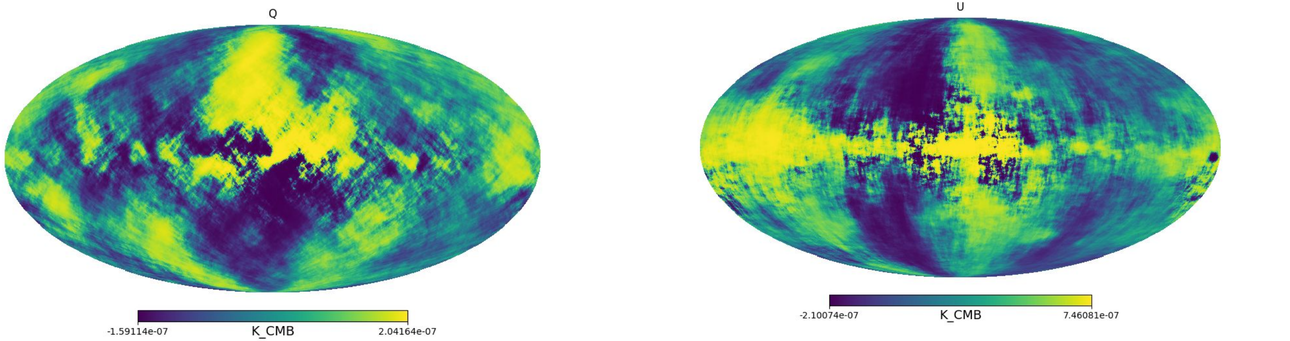


Residual maps from the TOD of only one detector

Input Sky maps



$$\boldsymbol{\Delta m}_1 = M_1^{-1}[P_1^T C_1^{-1} X_{12} t_2]$$



Power Spectra pi/4 common impedance